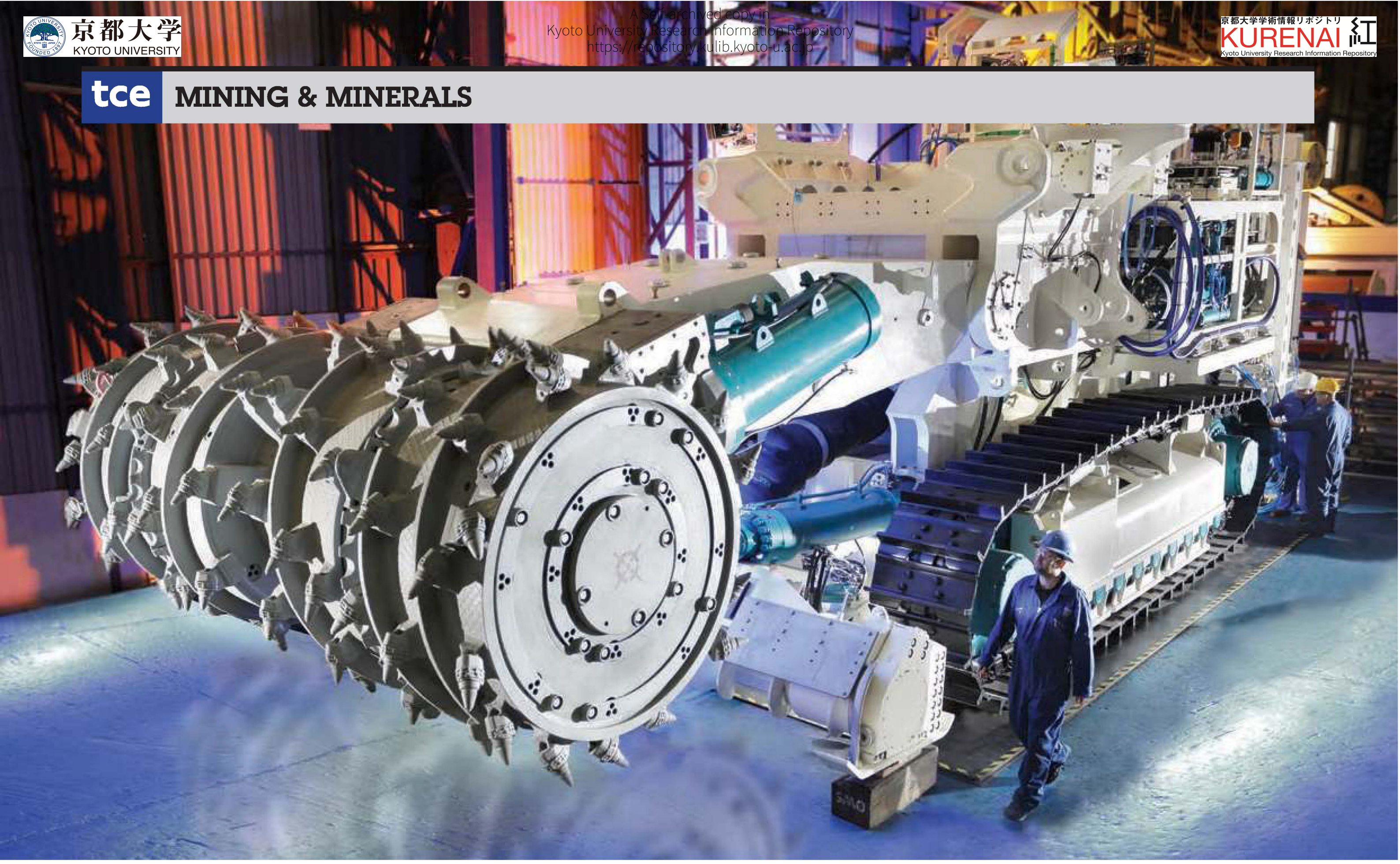

The final frontier

Benjamin McLellan discusses the challenges and opportunities for deep sea mining of minerals

THE deep ocean is one of the final frontiers for human activity, reflecting its vastness, remoteness and the difficulty of making observations – directly or remotely. Despite these challenges, recent high prices, increasing demand, concerns over scarcity, and the lure of high grades all make mining for minerals on the seabed an attractive proposition. And commercial reality appears closer than ever before, with companies and national corporations expanding exploration. Nautilus Minerals has gone so far as to gain approval to mine copper and gold – and potentially silver and zinc – at its Solwara I deposit off New Ireland, Papua New Guinea and aim to start production from 2018.

a rich supply

There are four main types of metalliferous mineral deposits on the seabed.

- **Manganese** nodules (also known as polymetallic nodules): these pebble- or potato-like nodules range in size from millimetres to tens of centimetres. They are formed by the precipitation of minerals from surrounding seawater minerals onto a hard substrate such as sharks' teeth. Their density is 5–15 kg/m^2 seabed and they are found at depths of ~4,000–6,000 m.
- **Cobalt**-rich crusts, and polymetallic crusts: these are hard layers of precipitated material similar to manganese nodules but formed in a continuous layer, like asphalt on a road surface. Commercially-considered deposits are typically 4–15 cm, and are found on the flanks of seamounts, ridges and undersea volcanoes, at a depth of ~800–3,000 m).
- **Seafloor massive sulphides** (SMS): these surface layered deposits and chimneys are formed around hydrothermal vents by the rapid deposition of hot sulphide materials exiting the vents and contacting the surrounding cold seawater. They are found at depths of ~700–2,400 m.
- **Metal-rich muds**: these are deep ocean sediments found in some cases with high concentration of target metals such as rare earths at depths of ~4,000 m.

Given that most of the ocean floor is still largely unknown and unmapped, it is difficult to estimate with any degree of certainty what the potential mineral resources are.

These deposits vary in how they're formed, the target metals and minerals they contain and the depth at which they are found. Many of these deposits are considered promising for their high grades in base and precious metals; target metals are typically copper, nickel, cobalt, zinc, gold, and silver with high contents of other metals such as manganese – particularly in the case of nodules and crusts.

Manganese nodules were discovered as early as the 1800s, when they were dragged up from the bottom of the ocean, while SMS deposits were, by chance, discovered in the late 1970s when a team of scientists tracking ocean temperatures noted spikes in their data. In both cases, these discoveries were originally of more interest from a scientific perspective than as an industrial opportunity

Nautilus Minerals

Neptune Minerals/ OceanFlore.

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(Left): Nautilus' bulk cutter leaves cut material on the seafloor for the collecting machinery; (above) Neptune Minerals' subsea mining system, SMS mining grab system being pilot tested in a chimney field at 1,200 meters, and material recovered from the seafloor.

– particularly the organisms found around hydrothermal vents. The recent growing interest in deep ocean mineral deposits is the second wave of commercial interest, with early exploration, equipment development and trials occurring from the 1960s through to the late 1970s.

However, while technology has enabled better understanding of sections of the deep ocean, there is still much that is yet to be understood – geologically and environmentally – and many barriers to full-scale economic and environmentally-sound mining. Given that most of the ocean floor is still largely unknown and unmapped, it is difficult to estimate with any degree of certainty what the potential mineral resources are.

technology and engineering

The technology required to mine, process, smelt and refine deep ocean ores varies significantly by ore type, but there are many components that are already well-known and well-tested in other industries or environments. Deep-ocean conditions are significant constraints on the performance and requirements of the technology, specifically:

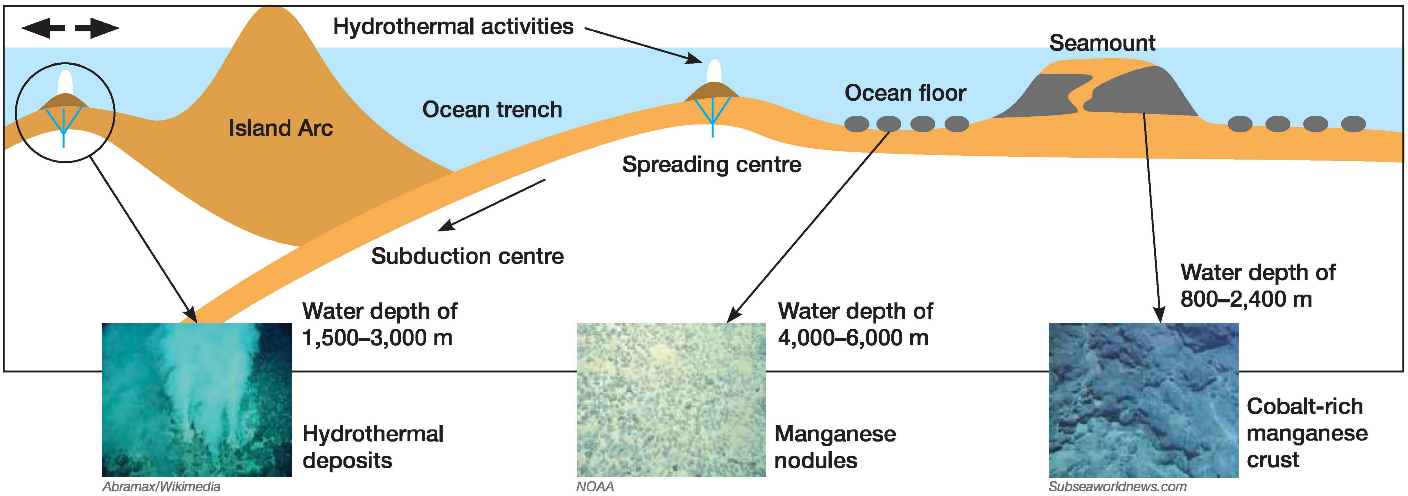
- high pressure environments – for a water column of 1,500–6,000 m, equipment needs to be able to withstand pressures in the order of 150–600 bar;
- low temperatures, typically 2–4ºC, sometimes in close proximity, though not planned to come in contact with, high temperatures, >350ºC; and
- constant and variable water movements including cross-currents and their variability from the top to the bottom of the water column. In addition, ship-board processing must deal with limitations on available space and the fluctuations produced by wave movement on the ship.

how's it done?

There are three stages of mining. Stage 1, mining the material on the seafloor, uses a seabed mining machine. In most modern projects these are assumed to be powered and self-driven, but there have been many experimental mining tools that were towed.

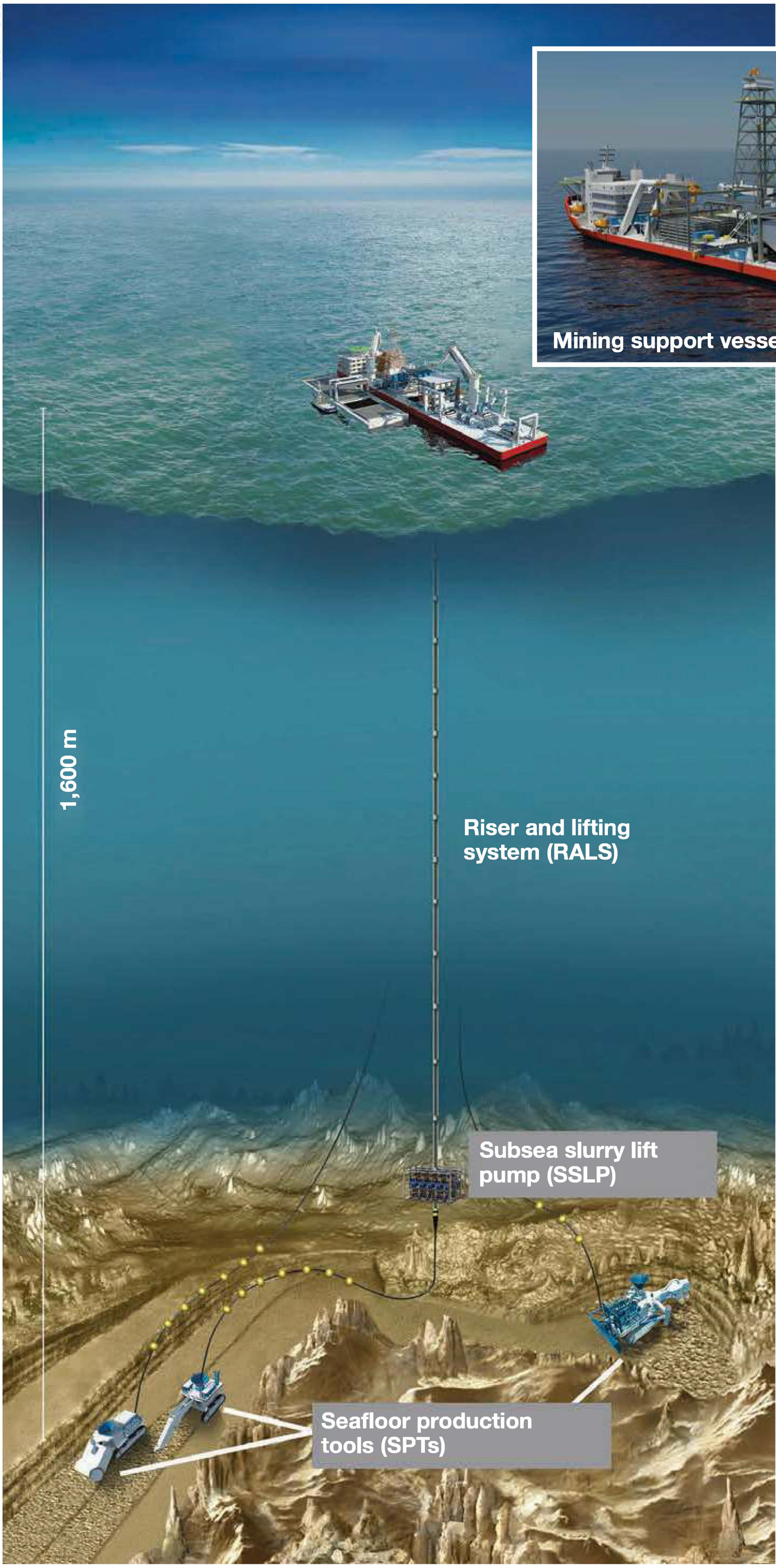
In nodule mining, the first challenge is to collect the nodules, which are partially buried in the seafloor. They vary in size from millimetres to tens of centimetres, requiring appropriate technology to separate them from the surrounding sediment in order to reduce the amount of material requiring transfer to the surface. A series of mesh buckets or nets drawn continuously by boats are one alternative proposed technology. In the case of crusts and SMS deposits, a mining machine must break the ore and extract it from the seabed. These miners need to deal with slopes and potential for becoming caught in sediment. In the case of Nautilus, it plans to have three mining tools – one to prepare the way, creating a more level bench for the main miner, which in turn removes the majority of material, crushing it and stockpiling it for collection and transfer with a third tool. The smallest of these tools weighs around 150 t. Other methods – such as *in situ* leaching and high-voltage impulse for the extraction of cobalt-rich crusts have been examined, but are not commonly considered at present. An

Spreading centre



Occurrence of deep-sea mineral resources

Nautilus Minerals



Nautilus Minerals

Seafloor production system, courtesy of Nautilus Minerals

entirely different system under consideration is Neptune Minerals' 'grab' system that picks up the material more selectively from the seafloor before transferring it to a vertical bucket-lift system.

Stage 2 involves the vertical transfer of ore to the surface. In general, seabed miners will crush the ore to a given screen size before transfer, typically by pump at a slurry concentration of 12–20%. There are a number of critical elements in the transfer stage: firstly, the first stage of transfer (through a flexible pipe that allows for the movement of the miner (without requiring the ship to move) and changes in depth or position; secondly, the pumping mechanism, which must have high reliability under the working conditions; and thirdly, the pipe structure itself, which must cope with stresses caused by cross-currents and the movements of the ship in the vertical direction, and the corrosion associated with slurry pumping. Currently, such pipes have a long vertical section that is reinforced with a number of vertical non-fluid-transporting pipes which also help protect and hold the communications and electrical cabling. Deploying these long pipelines takes days, as does retrieval, making weather vulnerability a concern to be monitored. Early trials (in the 1970s) had various pipe and cable failures – with losses of long sections of pipe due to joints becoming unfastened. Pipeline deployment has improved dramatically with the expansion of deepsea oil extraction, an industry employing many chemical engineers. Much of the knowledge applied to deep ocean mining transfer pipelines comes from this sector. Selecting and designing pumps to meet the operational requirements is also an important area for consideration. Positive displacement pumps that use the return water to provide some of the pump power, are being looked at by Nautilus, although others have considered airlift pump systems.

In Neptune Minerals' bucket-lift system, no pumps or pipelines are needed. A pair of cable-drawn buckets (several cubic metres in volume) hauls material to the surface and returns the unwanted water from the dewatering process. This vertical lifting stage is one of the largest energy-consuming components of the mining phase, making it an important candidate for improvement. Integrity of the transfer mechanism is also vital so that valuable material is not lost, and damage to the environment – particularly release of material in the upper ocean – is avoided.

After the ore has been transferred to the mining support vessel, stage 3 involves dewatering, and – typically – transferring the ore to shore for further processing. The dewatering process aims to reduce the water content to around 10% by weight, for more economic transfer and later processing. In the case of nodules, dewatering is not typically considered to be an onboard process.

There are a number of factors that need considering when it comes to dewatering on the mining support vessel. The ore needs to be dewatered effectively, while the return water needs to contain as little solid material as possible while not being over-heated or disturbing the balance of dissolved oxygen, which could impact on the deep sea environment. Systems of screens, cyclones and filters – typical of minerals processing operations – are the standard technologies applied, but consideration should be given to shipboard challenges such as the limits of space and reducing the vertical dimensions. Systems to transfer the dewatered material to barges or ships for transport to processing are also areas ripe for technological innovation.

Once the mining phase is finished, the material is transferred to processing. Depending on the minerals targeted and the specific ore, the processing techniques vary, but are largely the same as existing minerals operations. Shipboard processing is generally considered too difficult given the space limitations, the constant movement due to waves, and the potential risks associated with reagent spills, etc.

All ores are different, but in general, nodules and crusts have been considered for processing in similar manners to laterite ores, with hydrometallurgical and pyrometallurgical routes to extract primarily nickel, cobalt and copper. Manganese is more often considered only as a potential by-product although the grade is generally higher than the aforementioned metals.

Sulphide ores from SMS deposits are usually considered to be separated into lead-zinc and copper-gold concentrates via flotation, before further smelting, refining or electrowinning. One of the key problems that has been observed with some of these SMS ores is that the extremely fine particles and refractory nature of the ore make separation and recovery very difficult. There is therefore scope for further examination of appropriate flowsheets and technology to improve recovery. It is also important to note that some of these deep ocean ores contain high levels of contaminants such as arsenic and mercury which are likely to draw penalties from smelters accepting the concentrate. The tailings associated with these processes need consideration too, as unlike land-based mines, there is no land available at the mine site to store waste material.

sustainability

Assuming the technological hurdles can be overcome and the economic feasibility assured, the final (and some would argue most important) challenges for deep sea mining revolve around environmental impacts and social acceptance.

Regarding social acceptance, it is important to separate the location of deposits between: (a) those relatively close to shore (within the Exclusive Economic Zone) which are nationally controlled; and (b) those in international waters – 'The Area' that is distant from all major land masses and where mining rights are allocated via the International Seabed Authority (ISA). In the former case, project economics may be better due to proximity, but there could be directly-affected landholders or others with ocean rights. Achieving stakeholder acceptance for such projects may be argued to require a somewhat different approach to community engagement on land, as the delineation of traditional usage areas may be less clear, and the distinction between the deep ocean and the shallower depths used for fishing may become a point of contention. In the case of the deep ocean, the stakeholders are less clear, as nominally all citizens of the world have a stake. In this case, it is likely that some form of distributed responsibility for stakeholder engagement would be allocated to the nations who are signatories to the United Nations Convention on the Law of the Sea.

Regarding environmental impacts, like most mining activities it would be expected that an Environmental Impact Assessment (EIA) would be required before mining could take place. On a whole-of-supply-chain basis, the extreme depth of some deposits and the remoteness of those in The Area are two key considerations which are likely to be less-than-favourable in the comparison with terrestrial deposits. However, the high grades and lack of overburden may be beneficial for deep ocean mining. There are also a number of location-specific impacts that can only be assessed on a mine-by-mine basis – for example, the amount of seafloor disturbance (potentially large for nodule-mining or small for SMS and crust deposits); the impact of return-water and sediment disruption; the specific biodiversity impacts; and the amount and type of toxic waste elements in the ore or produced during

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processing (eg arsenic and mercury in the case of the Izena Cauldron, Japan).

EIA – the final frontier

Despite many studies and disturbance tests of the ocean floor indicating that it is possible to mitigate or offset many of the impacts on the environment (by setting aside untouched sections in the mining lease for example), there is still a high level of uncertainty as to whether these test study results will translate effectively to large-scale mining.

To date, phosphate mining off New Zealand has been rejected at the EIA stage, and for the bigger picture, the ISA has yet to finalise its EIA procedures for The Area. As part of the regulations for exploitation of international resources, a draft is expected by early 2016, but some countries are contending that the lack of sufficient data should push this deadline back by up to 24 months. Contrary to the international situation, some individual nations have relevant regulations in place – for example the government-accepted EIA for Nautilus` Solwara I project in PNG.

However, with Nautilus gaining the go-ahead to mine in PNG, many will be watching with interest. **tce**

Benjamin McLellan (b-mclellan@energy.kyoto-u.ac.jp) is associate professor at the Graduate School of Energy Science, Kyoto University

Chemical Engineering Matters

The topics discussed in this article refer to the following lines on the vistas of IChemE's technical strategy document *Chemical Engineering Matters*:

Water
Lines 13–14

Health and wellbeing
Lines 1, 6, 7 ,10, 11–12, 19

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